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Analysis of tourniquet pressure over military winter clothing and a short review of combat casualty care in cold weather warfare

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ABSTRACT
Cold weather warfare is of increasing importance. Haemorrhage is the most common preventable cause of death in military conflicts. We analysed the pressure of the Combat Application Tourniquet® Generation 7 (CAT), the SAM® Extremity Tourniquet (SAMXT) and the SOF® Tactical Tourniquet Wide Generation 4 (SOFTT) over different military cold weather clothing setups with a leg tourniquet trainer. We conducted a selective PubMed search and supplemented this with own experiences in cold weather medicine. The CAT and the SAMXT both reached the cut off value of 180mmHg in almost all applications. The SOFTT was unable to reach the 180mmHg limit in less than 50% of all applications in some clothing setups. We outline the influence of cold during military operations by presenting differences between military and civilian cold exposure. We propose a classification of winter warfare and identify caveats and alterations of Tactical Combat Casualty Care in cold weather warfare, with a special focus on control of bleeding. The application of tourniquets over military winter clothing is successful in principle, but effectiveness may vary for different tourniquet models. Soldiers are more affected and impaired by cold than civilians. Military commanders must be made aware of medical alterations in cold weather warfare.

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Introduction

Haemorrhage is responsible for roughly 90% of preventable deaths on the battlefield and is also the most common preventable cause of death in civil out-of-hospital emergency medicine [1–3]. In current world politics, conflicts in cold climate regions are again increasingly a focus for military medicine. In the Ukraine war, for example, cold exposure is a relevant medical problem causing cold injuries [4]. It is well documented that hypothermia worsens coagulation and deteriorates traumatic bleeding [5]. To our knowledge, no systematic review data exists on preventable causes of traumatic death in cold climates. Although each war is unique, it is reasonable to assume that external bleeding also plays a central role in preventable causes of death in such conditions. In addition, the cold has an influence on almost all medical measures in structured patient care.

Currently, no consensus recommendations exist for tactical care in cold environments. There is a paucity of data on the effectiveness of medical interventions in cold environments, including the application of tourniquets over clothing. We analysed the pressure of 3 different models of tourniquets over different military clothing layers. In addition, this article gives a short outline on the influence of cold for military operations and military planning. As a basis for further discussion and development, it identifies specific cold-related issues of Tactical Combat Casualty Care (TCCC) in cold weather warfare.

Methods

We analysed the application of 3 different models of windlass tourniquets recommended by the Committee on Tactical Combat Casualty Care (CoTCCC) [6]:

- Combat Application Tourniquet® Generation 7 (CAT)
- SAM® Extremity Tourniquet (SAMXT)
- SOF® Tactical Tourniquet Wide Generation 4 (SOFTT)

20 measurements of two experienced providers (AO, YB) were conducted over the undressed trainer and

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various military clothing (Tables 1 and 2) consisting of different combinations of the following clothes:

- Bundeswehr Combat Uniform trousers (CombTr)
- Bundeswehr Uniform insulation sublayer (InsSub)
- Bundeswehr Uniform rain trousers (RainTr)
- Bundeswehr Uniform insulation trousers (InsTr)

Pressure was measured with the Hapmed™ Tourniquet Trainer (leg number 0082, v2.17.25), an artificial thigh that measures the pressure of applied tourniquets. The trial was performed at room temperature. The tourniquets were all applied ambidextrously and no gloves were worn. The subjects were blinded to the display of the tourniquet trainer. The measurements were performed first with the CAT, then the SAMXT and then the SOFTT, the order of the clothing setups was analogous to the order of Table 1. Effectiveness was defined as a pressure higher than 180 mmHg, defined by the CoTCCC as the lower limit of the optimal occlusion pressure of tourniquets [6]. Arterial occlusion is supposed to be achieved in a severely injured patient in permissive hypotension, with a tourniquet pressure of 180 mmHg, which is 100 mmHg over systolic blood pressure in that situation.

The trial is no human subject research. Therefore, no ethics approval was necessary according to the ethics committee of the University of Ulm.

Additionally, we conducted a selective PubMed search with articles until 31.12.2022 with the keywords "haemostatic dressing"/"tourniquet"/"tactical combat casualty care" and "cold"/"hypothermia" and screened the abstracts for eligibility. We also manually searched the reference lists of eligible articles for other relevant publications. Our personal experience as soldiers, emergency physicians and military mountain guides was also incorporated into the recommendations of this article.

Results

The number of measurements above the 180 mmHg cutoff is presented in Table 1. The CAT achieved a sufficient compression pressure of more than 180 mmHg in all applications. The SAMXT achieved a sufficient compression pressure of more than 180 mmHg in all but one application. The SOFTT achieved a sufficient compression pressure of more than 180 mmHg in 73 out of 120 applications. In 3 clothing setups the success rate of the SOFTT was below 50% (InsSub + CombTr; CombTr + RainTr; CombTr + InsTr + RainTr).

Discussion

Tourniquet application over military winter clothing

Our data suggest that the application of tourniquets over military clothing is successful in principle but may depend on the tourniquet model. It is noticeable that the SOFTT primarily generated pressures below 180 mmHg when clothing layers with a low compressible, but smooth low friction surface, were used (InsSub, RainTr). An interaction of the tourniquet surface texture with these layers seems plausible but cannot be quantified. Low friction surfaces have the potential risk of tourniquet dislocation distally towards the slimmer portion of the limb due to strap sliding [7].

In scenarios without direct threat, both military and civilian guidelines recommend applying the tourniquet 2–3 inches/a hand's width above the wound directly on the skin [8,9]. In dangerous situations (e.g. care under fire scenarios), in darkness, in challenging environmental conditions, under pressure of time (e.g. mass casualty incidents) or if a patient's extremity cannot be reached (e.g. motor vehicle accident with trapped person) a tourniquet can be applied more proximal and over the clothing (high and tight approach) [8,10]. There is little data on the placement of tourniquets over winter clothing. Several studies evaluated the application of tourniquets over clothing, mainly over combat trousers and CBRN trousers, but only one study analysed a winter warfare configuration [7,11–13]. There was no significantly increased failure rate in the winter warfare configuration compared to the control group [13]. Two studies recorded recipient discomfort and pain and found that application over clothing was less painful, presumably due to

Table 1. Number of applications with pressure over 180 mmHg out of 20 applications over different clothing setups (CAT: Combat Application Tourniquet® Generation 7, SAMXT: SAM® Extremity Tourniquet, SOFTT: SOF® Tactical Tourniquet Wide Generation 4).

Clothing setup	CAT	SAMXT	SOFTT
undressed	20	19	17
Bundeswehr Combat Uniform trousers	20	20	18
Bundeswehr Uniform insulation sublayer + Bundeswehr Combat Uniform trousers	20	20	4
Bundeswehr Combat Uniform trousers + Bundeswehr Uniform rain trousers	20	20	9
Bundeswehr Combat Uniform trousers + Bundeswehr Uniform insulation trousers	20	20	17
Bundeswehr Combat Uniform trousers + Bundeswehr Uniform insulation trousers + Bundeswehr Uniform rain trousers	20	20	8

less skin pinching [7,12]. This can be viewed as an advantage since pain can be an indirect indication of pressure damage. In general, the application of the tourniquet appears to be more tolerable in the injured patient with the clothing layers providing some form of padding [12]. Two of those studies compared the CAT with the SOFTT [7,13]. They found that the CAT was significantly more effective, generated more pressure and had less applier inability with closing the tourniquet over various clothing setups.

Military missions in cold environment

Cold exposure affects civilians and soldiers in general. However, similar to altitude exposure, soldiers (and civilians in war zones) are more affected and impaired by cold than civilians outside conflict areas (Table 2) [14]. That is why some authors combine mountain and cold weather warfighting as one entity [15].

Classification of winter warfare

Military leaders inexperienced in cold weather often underestimate its effects [14]. High altitudes are always associated with reduced temperature. The basic rule for the course of temperature at altitude is that at each 1000 m of altitude gain, the temperature decreases by 6.5°C [16]. A classification of cold levels may facilitate the operational planning process (Table 3). The wind chill temperature is a more important factor than the measured ambient temperature. The pivotal factor for the effects of cold on the body is the respective tissue temperature. When the skin is wet and exposed to wind, the ambient temperature, as used in wind chill tables, should be 10°C lower than the measured air temperature. Wind chill tables are based on the effect of cold on cheek skin. For fingers, the time to freezing is about 8 times less [17].

At tissue temperatures below 28°C, strength, power, endurance, and joint mobility decrease, and at temperatures below 20°C, nerve conduction velocity decreases. Below a skin temperature of 15°C, dexterity decreases with a cessation of sensitivity from below 8°C. Air temperatures of 10 to 16°C result in maximum vasoconstriction and insulation [17]. The risk of local cold injuries and hypothermia increases with decreasing temperature. Even at temperatures above freezing, non-freezing cold injuries may occur. The effects of cold have caused significantly higher casualty rates than injuries from military opponents in some campaigns [14]. However, the basic prevention and treatment options do not differ from civilian recommendations [18,19].

Summary observations about medical care in the cold, based on real life experience

Although based on the same principles, tactical casualty care must be adapted in cold environments. Tactical casualty care is generally divided into 3 phases [8]. The first phase, care under fire, describes care under fire/threat, without specifying the threat in greater detail. The only medical procedure here is the application of a tourniquet. Cold and intensifying environmental factors

Table 2. Differences between cold exposure in civilian and military circumstances.

Objective	Civilian	Military
Preparation time	Long preparation time	Potentially with short notice
Freedom of movement	Unlimited	Limited
Time in cold	Rather short	Potentially long (mission accomplishment)
Shelter option	Mostly given	Maybe limited, depending on the tactical situation
Criteria to terminate activity in the cold	Own choice	Mission accomplishment
Performance requirement	Adaptable	Full combat strength needed
Clothing	Optimal insulation possible	Predominantly military equipment used Optimal insulation not guaranteed
Dexterity	Predominantly non-mandatory	Mandatory to handle military equipment and weapons
Use of heat sources	Whenever available	Maybe limited, depending on the tactical situation
Chain of evacuation and medical treatment	Established	Limited

Table 3. Different types of warfare. Adapted after Lechner at al [14]. FCI: Freezing cold injuries, NFCI: Non-Freezing cold injuries.

Type of warfare	Wind chill temperature	Relevant cold injuries	Risk of cold injury
damp weather warfare	15–0°C	NFCI possible	
cold weather warfare	0 – −30°C	FCI possible	
arctic warfare	Less than −30°C	FCI in exposed facial skin within 10 to 30 minutes for most people	

such as wind and moisture are to be considered as an independent direct threat to the casualty in cold weather warfare and require therefore adapted treatment algorithms [20–23]. The Mountain Rescue Austria, for example, has defined *cr* in its *crABCDE* algorithm as a “critical situation” in which severe external bleeding is controlled and life-threatening hypothermia is addressed from the beginning of patient care [24–26].

The second phase, tactical field care, can only be transferred to when all direct threats have been cleared. In cold weather warfare, this means that the influence of the cold has been eliminated, or at least been reduced. This can be achieved, for example, by portable lightweight emergency bivvy shelters or rapid transport to an area protected from environmental hazards. In this case, the treatment is carried out according to the MARCH/<C>ABCDE algorithm, which, however, must also be modified depending on the remaining extent of the cold and the planned evacuation modality (= phase 3, Tactical Evacuation Care).

It should be noted that the cold also has effects on the medical provider. Thus, of course, dexterity also decreases [21]. In addition, the rescuer, who can move and is under stress, has a different sensation of temperature. While the patient already feels the cold and may no longer be able to express it, the rescuer feels warm and thus underestimates the level of cold. The patient also cools down much faster than the rescuer due to a large contact surface (conductive heat loss).

Clothing should be removed for the examination only for as short a time as possible and only at the point that must absolutely be exposed [23]. This poses an increased risk of missed injuries [21]. Once the appropriate part of the body has been exposed, all the necessary measures should be carried out at once on a cardiorespiratory stable patient (examination, therapy, improvement of insulation). If transport to a sheltered area is expected to take longer than 30 minutes, very wet clothing should be removed (cut open) and replaced with dry clothing. Damp clothing should be left in place and insulation should be optimised with a vapour barrier [18].

Treating critical bleeding (“M”/“<C>”;) can be achieved by pressure dressing, (junctional) tourniquets, and wound packing with haemostatic agents, as recommended in both, TCCC and civilian guidelines [3,8]. Up to 1/3 of all potentially survivable haemorrhages in military conflicts affect the extremities and are amenable to tourniquets and about 20% are in junctional regions (groin, axilla, neck) and can potentially be treated by wound packing with or without additional haemostatic agents [1]. The Case Fatality Rate and the Killed in Action rate are potential measures of effectiveness of prehospital care and are decreasing constantly in military conflicts since World War II [27]. Tourniquets are estimated to have prevented 474 additional deaths in the U.S. forces in the Afghanistan and Iraq conflicts between 2001 and 2017 [28]. The effect of haemostatic agents is scientifically less evident. A direct comparison of tourniquets and haemostatic agents shows that tourniquets are easier and faster to apply, require less training, and that potentially fatal injuries that can be adequately controlled with a tourniquet alone are more frequent than those requiring a haemostatic dressing.

However, the applications of tourniquets must be considered carefully in cold weather warfare, as reduced blood flow is associated with an increased risk of FCI [19,23]. A tourniquet, which was not necessary, dramatically increases the risk for FCI throughout the extremity distal to the tourniquet. It is usually not possible to apply a tourniquet to the skin, but, according to our data, an application over clothing is efficient. Wearing thermal gloves resulted in significantly slower tourniquet placement and significantly higher blood loss compared to bare hands [29]. Without gloves, there is a cold-induced loss of dexterity and strength [17], which also makes application more difficult and cold temperatures therefore significantly increase the application time of tourniquets and thus the time to haemorrhage control [30]. This applies not only to haemorrhage control but to medical interventions in general.

Studies attest that both kaolin-based and chitosan-based haemostatic agents are effective in mild hypothermia [31–34]. However, there are no comprehensive comparative studies between those products, so that no product can be clearly recommended as superior. In very cold conditions, a wound packing requires a long and extensive exposure of both the wound and the practitioner (trying to work with fine motor skills for a longer period). Applying an adequate pressure dressing over clothing left in situ for cold protection to secure a packed wound is also challenging. Therefore, tourniquets seem to be the key factor in reducing preventable deaths in cold weather warfare.

When it is necessary to secure the airway (“A”), the tubes used can be very stiff due to the cold, frozen plastic edges can even cut tissue and thin plastic parts, e.g. a cuff, has a considerable risk of tearing. An inflation of a cuff with cold air will cause high cuff pressures with risk of rupture because the inflated air will warm and expand and cold tubes may cause FCI at the point of contact [18,21]. Freezing of condensation water may cause equipment dysfunction and tube/heat moisture filter obstruction [22,35]. If the patient is not in respiratory distress, a cold air mask or, if not available, a scarf should be placed over the external airway, to better pre-warm the inhaled air. When available, oxygen should be used to reduce the risk for FCIs at altitudes above approximately 4,000 m [19].

When addressing "R"/"B" problems, chest seals may freeze and crack [21]. However, the adhesion of most chest seals is sufficient in cold conditions [36]. During the examination of the back (normally performed during the examination of the posterior thorax as part of "R"/"B"), a vapour barrier (e.g. rescue blanket) should be placed above the innermost layer of clothing. Turning the patient should be used to slide a well-insulating pad, placed on a carrying gear, under the patient [8]. Ideally, this should already be within a hypothermia enclosure wrap (see "H"/"E"). Heat packs should be placed on the upper body and in the axilla without direct skin contact to avoid burning [8,18].

For "C", a modified blood sweep may need to be performed. Due to multiple layers of clothing, it may be impossible to examine the skin directly. However, in this case, blood should be looked for under the innermost water repellent layer of clothing. The outer clothing should be carefully searched for penetrating injuries. Since several layers of clothing may not show blood on the outer layer of clothing in the early stages, this may be an indicator of penetrating injuries. In addition to holes, leakage of insulation material is indicative in this case. Such areas of the body, or areas where the patient reports severe pain, should be examined in detail, possibly also by cutting open small areas of the clothing. A second vapour barrier (e.g. rescue blanket) should be placed from the front above the innermost layer of clothing, because the vapour barrier on the back often cannot be wrapped sufficiently around the front of the body. Due to peripheral vasoconstriction, pulse oximetry is often not feasible. Improvement can be achieved by good insulation of the hands. Peripheral capillary refill time is also often not suitable. Similarly, venous access is significantly more difficult because of vasoconstriction. If drugs are required, other types of administration must be considered (transmucosal, intranasal, intraosseous, oral). Because infusions freeze quickly, an infusion warmer should be used and/or the liquid should be administered as a bolus and not as a continuous infusion [8,18]. Cold infusions will worsen hypothermia [37]. Therefore, intravenous fluids should be restricted to vital indications.

For "H"/"D" it must be considered that traumatic brain injury, severe blood loss and hypothermia as well as severe acute mountain sickness/high altitude cerebral oedema can cause altered mental status. The head, face and neck area must be carefully isolated, by using a balaclava for example.

Regarding "H"/"E", the insulation must be carefully optimised to prevent cooling during long transport.

Table 4. Treatment algorithm with cold weather adaptions. FCI: freezing cold injury; i.V.: intravenous; i.O.: intraosseous, i.N.: intranasal; t.M.: transmucosal; AMS: acute mountain sickness; HACE: high altitude cerebral oedema.

MARCH/ <C>ABCDE Algorithm	Cold weather caveats	Cold weather adaptions
Massive hemorrhage/ critical bleeding	• high risk of FCI in distal limb after tourniquet application	• Application over clothing
Airway	• Stiffness of plastic tubes, tearing of cuffs, FCI on contact points	• Periodic cuff pressure controls • Use cold air masks and apply oxygen
Respiratory/ Breathing	• frozen chest seals may crack	• Place a vapour barrier above the innermost layer of clothing at the back during "check the back" examination • Place an insulating pad within a hypothermia enclosure wrap on a carrying gear under the patient during "check the back" examination • Place heat packs on chest and/or axilla (avoid skin contact)
Circulation	• high risk of FCI in distal limb after tourniquet application • High failure rate with pulse oximetry and peripheral capillary refill time due to peripheral vasoconstriction • Difficult venous punction due to vasoconstriction • Freezing of i.v. fluids	• Checking for blood under water repellent layer, if skin cannot be touched (blood sweep) • Checking for damage of insulation clothing (visible padding material) • Place a second vapour barrier above the innermost layer of clothing from the front • Use of alternative drug delivery methods (i.o., i.n. t.m., oral) • Use i.v. heating systems or, if not available, apply fluid in boluses
Head/Disability	• Hypothermia, AMS, HACE may reduce mental status	• Careful head and neck insulation
Hypothermia/ Environment	• Hypothermia compromises coagulation	• Optimisation of insulation for transport

Commercially available thermal protection systems are not sufficient and must be reinforced by insulation layers (e.g. hooded sleeping bag) and an internal vapour barrier [8,38]. Because valid preclinical body temperature measurement is very difficult, history and clinical assessment according to the Revised Swiss Staging System should be used to diagnose hypothermia. In this system, the stage of hypothermia is classified according to consciousness using the AVPU scale (alert, verbal, pain, unresponsive) [37,39]. Trauma related confounders must be considered. Adaptations of patient care in cold weather warfare are summarised in Table 4.

In general, it should be noted that metal objects can cause FCIs when touched and that one can freeze to them in combination with moisture (metal laryngoscope, needles, monitoring systems). Batteries have much shorter run times and monitoring systems may not work at all in very cold conditions. Spare batteries and medications need to be stored warm (heating box, body worn). Lithium batteries should be preferred whenever applicable. There is also the possibility that equipment may no longer function at cold temperatures due to increased stiffness or breakage of plastic parts.

Since the examination of the patient is much more difficult, a close re-evaluation must be carried out. As soon as a suitable location is reached where a standardised patient examination is possible, this must be followed up.

Conclusions

Cold weather warfare, especially in combination with high altitude warfare, is of increasing importance. Tourniquet application over winter warfare clothing is effective but varies between different models of tourniquets. Adapted treatment algorithms and tactics, techniques and procedures for cold environments are requested by many experts, because cold, especially with aggravating factors as wind and moisture, pose a direct threat. However, proposed adaptations are poorly supported by studies and are almost exclusively expert opinion. Thus, medical care in cold weather warfare is of high priority for research funding and future work to determine whether adaptations in patient care can improve the overall outcome. The suggestions presented in this article serve as a basis for discussion in order to optimise the treatment of injured patients under cold climatic conditions.

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Author contributions

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Concept and design (RL), First draft (RL), literature search (RL, YB, BH), tourniquet measurements (AO, YB, KB, RL), data analysis (RL), critical review (MT, BH), approval of final version (all).

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